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"A Study of the Response of Upper Atmosphere Parameters to Variations of Solar Activity"

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Final Report

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In our original contract proposal to NASA we outlined a plan of analysis of observed upper atmosphere parameters (i.e., ozone, temperature, etc.) as they vary in response to changes in full-disk solar UV irradiances over solar rotation and solar cycle periods. The plan was to use data derived from different operating observatory systems, both ground based (umkehr, ozonesonde, etc.) and satellite (SBUV, SME, etc.) and to extend this analysis to UARS observations after launch. In addition, we planned to make use of 1-D and 2-D radiative-photochemical-dynamic models in attempts to understand the mechanisms which contribute to upper atmospheric responses to solar irradiance variations. The results of our investigation are briefly summarized below. A list of papers presented at scientific meetings and papers published in journals and scientific proceedings discussing these results is given in the appendices.

1. Analysis of Solar Variability

Our early studies concentrated on analyses of solar UV irradiance observations from Solar Mesosphere Explorer (SME) measurements. Our preliminary investigation involved documentation of the irradiance variation over 20 solar rotation periods (December 1981–June 1983) during the early part of the declining phase of cycle 21. When the full set of SME solar observations (January 1982–April 1989) became available, we could evaluate both the long-term (solar cycle) and short-term (solar rotation) variations. During the period of solar decline (1982–1987) the average irradiance decrease was approximately 55% at Ly-α, 6% at 200–205 nm, and with decreasing changes at longer wavelengths becoming less than 1% at 295 nm. These are spectral intervals that play dominant roles in the photochemistry and thermal energetics in the mesosphere and stratosphere. For the declining phase of cycle 21 the correlation of 27-day smoothed values of F 10.7 cm flux with irradiances at different spectral intervals was +0.91 (Ly-α) and +0.88 (200–205 nm) decreasing to +0.45 (280–300 nm) indicating a measure of the reliability of using F 10.7 cm flux data as a proxy set for solar radiative energy input to the upper mesosphere, lower mesosphere and mid-stratosphere for evaluating the extent of upper atmosphere responses to solar variability.

For the spectral interval 195–300 nm the irradiance minimum occurred in early 1987, about six months later than the minimum for Ly-α and about 18 months later than that for F 10.7 cm. This phase delay requires minor adjustment in evaluating stratospheric and upper mesospheric responses to the spectral distribution of solar energy input variations when using F 10.7 cm data as proxy for relevant solar forcing.

At the peak of solar cycle 21, the amplitude of the 27-day solar irradiance variation is about 12% at Ly-α and 2% at 200–205 nm but these amplitudes decrease strongly to approximately 5% at Ly-α and 0.5% at 200–205 nm at the time of minimum activity. Except under unusual circumstances, as will be noted in section 2, the 27-day irradiance amplitude at wavelengths generally longer than about 270 nm are difficult to document with the precision of instruments currently in use.

Our detailed analysis of solar irradiance variations continued with the launch of UARS in September 1991. We were able to make use of the ongoing SOLSTICE data covering full-disk solar irradiance measurements over the spectral interval 119–420 nm. Long-term calibration of the SOLSTICE measurements are made through comparison with observations from a group of bright early-type stars by using the same optical system as that used for solar observations. During the first 244 days of the SOLSTICE observing period, the early declining period of cycle 22, the average relative amplitudes of the short period (27-day) irradiance variation were similar to those derived from the SME observations for the peak period of cycle 21. By the end of the first year of UARS observations solar activity had declined from near peak to a moderate level and the relative amplitude of the 27-day solar irradiance oscillation was reduced by about a factor of two at all wavelengths below 260 nm. The values derived from the UARS SOLSTICE observations were subsequently used in our theoretical models of stratospheric and mesospheric ozone and temperature responses to strong short-term irradiance variations.

The results summarized above were reported and discussed in London et al., 1984; Rottman and London, 1984; London and Rottman, 1990; Pap et al., 1990; Pap et al., 1991; London et al., 1992; London et al., 1993; and London, 1994.

2. Observation of UV and Solar Constant Variations

(a) Contributions of solar UV to solar constant variations.

A total of about 1% of the average solar constant is contained at wavelengths $\lambda \leq 300$ nm. During the descending phase of solar cycle 21 and the ascending phase of cycle 22 satellite observations using well-calibrated cavity radiometers indicated a solar cycle variation of the solar constant of approximately 0.1%. We made use of the SME observations during January 1982–April 1987 to determine the contribution of the observed solar UV irradiance decrease to that observed for the solar constant. During the declining phase of cycle 21 (1982–1986) the decreased irradiance in the spectral interval 250–300 nm contributed approximately 30% to the reduced solar constant. An analogous but somewhat smaller positive contribution was made during the short period for which SME observations were available during the ascent portion of cycle 22. The major contribution of solar UV irradiance changes to long-term change of the solar constant is at wavelengths where the energy is absorbed (i.e., the lower and mid-stratosphere). This could have important consequences for the radiation budget at these stratospheric levels and needs to be included in models of solar influences on climate variations when the solar constant is used as the principal forcing function.

(b) Short-period solar UV and ozone variations related to solar constant.

For short periods (27-day) the nature of the spectral distribution of the full solar disk emission varies according to a complex distribution of sun spots, plage areas, and the configuration of the solar magnetic field. As discussed above, solar UV and solar constant variations are closely linked over long periods (i.e., solar cycles). But this is not generally so if isolated contiguous sunspot areas are the dominant manifestations of solar activity.

During the declining phase of cycle 21, we were able to identify ten occasions when observations made by both ACRIM and ERB measured distinct changes of total solar irradiance (solar constant) during the 13.5-day passage of single sun spot groups across the solar disk. A composite of the daily irradiance values for these ten events arranged over 30-day intervals (superposed epoch analysis) showed a significant decrease followed by an increase in the 13 days centered at central meridion passage with a range of 0.11% of the mean of the shoulder values for these periods. For these ten cases we analyzed the UV irradiance variations as measured by SME at Ly-α and 5-nm spectral intervals 200–300 nm. The averaged relative change was: 9% for Ly-α, 1.3% for 200–205 nm, and 0.4% for 290–295 nm. The correlation between the solar constant and UV values at these wavelengths, with 2σ significance, were -0.80, -0.85 and $+0.90$ respectively. The shift from negative to positive correlations occurred at about 270 nm, consistent with the different levels of the emission source at these wavelengths. We also calculated the ozone variations in the upper stratosphere and mesosphere as derived from SME observations over equatorial latitudes for the same ten events. The correlation between the solar constant values and ozone mixing ratio was negative at all levels in the upper stratosphere and lower mesosphere with a maximum value greater than -0.8 at 56 km (i.e., increased ozone with decreased total solar irradiance). Thus, the relationship between ozone variations in the lower mesosphere and short-period (solar rotation) changes of the solar constant is clearly a function of the level and pattern of solar activity.

The results summarized above were reported in London and Rottman, 1989; and London et al., 1989.

3. Theoretical Study

A principal motivation for our UARS study was to model and verify the upper atmospheric response to solar variability. For this purpose we developed a series of steady state and time-dependent 1-D and 2-D photochemical-radiative-dynamic models involving the interacting O_x, HO_x, NO_x, and ClO_x chemical families. For the short-term (27-day) response, we used the 1-D model applied to tropical latitudes with temperature feedback and a spectral distribution of solar irradiance as derived from SME or SOLSTICE observations during periods of high solar activity. A diagnostic study applying the 1-D photochemical-radiative-dynamic model to our preliminary calculations indicated the dominant influences of input irradiance at different spectral intervals and of different chemical families in affecting positive or negative responses at different atmospheric levels to imposed short-term solar variability.

The model results for short-term variations agreed fairly well with satellite derived observations. It was shown that temperature feedback played an important role in damping the amplitude and retarding the phase of the ozone changes particularly in the upper stratosphere. The model was also able to verify the dominant role of the HO_x system involving ozone perturbations in the upper mesosphere and lower thermosphere. A 2-D model which included horizontal transport of heat, momentum and trace gas concentrations between mid and tropical latitudes significantly improves the model results at all levels. However, an ozone deficit in the model was still present in the lower mesosphere.

The 2-D model was also used to compare the height and latitude ozone and temperature variations over the solar cycle. For this purpose equilibrium distributions were calculated with solar spectral irradiance values taken for solar maximum and minimum conditions from SME observations. As expected, the model calculations showed an ozone decrease of about 12% at 70–75 km as a result of increased Ly-α irradiance and increased H_2O at this level, and consequent ozone destruction resulting from a 20% increase in OH. In the upper stratosphere there is a calculated small ozone increase associated with O_2 dissociation in the Schumann-Runge bands and the Hertzberg continuum. The model results give a small positive temperature change with increased Ly-α at 70 km and a larger positive change, approximately 2 K at 45 km, over equatorial regions due to increased irradiance in the Hartley band. These results are approximately verified by long-term ozone and temperature observations in the stratosphere, but are not consistent with temperature observations in the mesosphere.

The theoretical studies were presented by Chen et al., 1993 and published in Chen et al., 1994; and Chen et al., 1996.

4. Diurnal Variation of Ozone in the Mesosphere

In an attempt to resolve some of the differences between the theoretical and observed ozone distribution in the mesosphere, we made use of the observed diurnal variation of ozone at levels of 50–75 km where the fast O_x-HO_x photochemistry is dominant. We compared the observed ozone concentration as derived from the UARS MLS 183 GHz measurements with the results of our 1-D model applied to the mesosphere at equatorial latitudes. The comparison of the observed and theoretical vertical distribution showed good agreement with abrupt decrease of ozone during the sunrise period and increase of ozone during sunset. The model still indicates a slight ozone deficit during the daytime at all levels and an ozone excess in the layer 60-70 km during the night. Both observed and theoretical distributions give maximum diurnal amplitudes at 65 km: about 0.7 ppmv (observed) and 1 ppmv (theoretical). This difference indicates that, at least at the equator, the water vapor concentration in the upper mesosphere might have been overestimated and the vertical diffusion of O_x and H_2O in the mesosphere may have been underestimated.

Some of these results were presented in London et al., at the AGU meeting 1993, and published in London et al., 1995; and London et al., 1996.

5. Perturbations of Upper Atmosphere Variables

Soon after SME launch in 1981 one of the instruments, the Infrared Radiometer, was able to continuously measure the 6.8-μm thermal emission from the El Chichon volcano starting at the time of its eruption in April 1982. The observational results show that the aerosol increased in mass to a maximum of 8 Tg about fifteen weeks after the 4 April eruption. Analysis of the development of the aerosol cloud extended through the end of 1986. Although the bulk of the cloud mass was contained in the latitude band from 10°S to 30°N, some transport of volcanic material to higher latitudes of both hemispheres is apparent in the derived data. The experience gained from the SME observations and analysis following the El Chichon eruption led to the establishement of a UARS Aerosol Working Group for the period 1987–1990 headed by Dr. Gary Thomas. The Working Group meetings raised the awareness of the UARS team in preparing for the likely eventuality of a major volacanic eruption occuring during the UARS mission. Contributions resulting from the group activities were productive since the major Pinatubo eruption in 1991 preceded the UARS launch by only three months and subsequent aerosol interference was present in all optical sensors well into 1993.

These results were reported in Thomas et al., 1983; Rusch et al., 1994; and Eparvier et al., 1994. A paper on the Pinatubo aerosols is in preparation (Massie et al., 1996).

A collaborative research program with NASA colleagues, started in 1989, made use of data derived from SBUV and SME observations to study the long-term variations of polar mesospheric clouds and their possible association with Ly-α variations over the solar cycle. These preliminary results were reported at the IAMAP Assembly in 1989. This study led to a program of analysis of solar forcing of mesospheric properties (i.e., water, temperature, and ozone) by solar Ly-α. Increased Ly-α irradiance at the time of solar maximum should result in increased dissociation of H_2O and consequently a decrease in the O_3 concentrations. The results of HALOE observations tend to support this relationship. That is, in agreement with model calculations, there is a decrease of H_2O at levels 65–80 km with an increased Ly-α, and an ozone decrease at 65–77 km. However, in the upper mesosphere, there is still some disagreement between the observations, which show maximum heating, and 1-D and 2-D model results which show minimum heating.

These results were presented at three meetings ISEA, 1995; IUGG, 1995; and AGU, 1995, and were published by Thomas et al., 1995.

APPENDIX 1
Papers Presented at Professional Meetings and Workshops Supported by NASA Grant No. NAS5-27263

"Eighteen months of UV irradiance observations from the Solar Mesosphere Explorer." J. London, G. J. Rottman, and G. G. Bjarnason. Middle Atmosphere Symposium, XVIII IUGG General Assembly; Hamburg, FRG. August 1983.

"Solar UV irradiance variations as derived from SME observations." J. London and G. J. Rottman. American Geophysical Union; San Francisco, California. December 1986.

"The contribution of solar UV irradiance variations to variations of the solar constant."J. London and G. J. Rottman. International Radiation Symposium; Lille, France. August 1988.

"Observed solar near-UV variability: A contribution to variations of the solar constant." J. London, J. Pap, and G. J. Rottman. Workshop on Solar Activity Forcing of the Middle Atmosphere; Liblice, Czechoslovakia. April 1989.

"Solar UV spectral irradiance data." J. London, G. J. Rottman, B. G. Knapp, and R. F. Donnelly. IAMAP 89, Fifth Scientific Assembly; Reading, United Kingdom. August 1989.

"Observations of Polar Mesospheric Clouds from the Nimbus-7 Spacecraft." G. E. Thomas and R. D. McPeters. IAMAP 89, Fifth Scientific Assembly; Reading, United Kingdom. August 1989.

"Wavelength dependence of solar rotation and solar cycle UV irradiance." J. London. NASA Conference on the Climate Impact of Solar Variability; Greenbelt, Maryland. April 1990.

"Latitude and seasonal variations of observed tropospheric ozone." J. London and S. Liu. XX General Assembly of the International Union of Geodesy and Geophysics; Vienna, Austria. August 1991.

"Our changing atmosphere—A problem of societal concern," *invited lecture*. J. London. ETH; Zürich, Switzerland. November 1991.

"Evolution of understanding of the middle atmosphere," *invited paper*. J. London. American Meteorological Society; Atlanta, Georgia. January 1992.

"Long-term observed ozone trends in the free troposphere and lower stratosphere." J. London. 1992 Quadrennial Ozone Symposium; Charlottesville, Virginia. June 1992.

"Variations of solar ultraviolet irradiance derived from SOLSTICE (UARS) observations." J. London, G. J. Rottman, and T. N. Woods. International Radiation Symposium, Tallinn, Estonia. August 1992.

"Observed solar UV irradiance variations of importance to middle atmospheric energetics and photochemistry." J. London. World Space Congress–COSPAR; Washington, D.C. September 1992.

"Las ciencias de la atmosfera y el cambio global," *invited lecture*. J. London, Union Geofisica Mexicana; Puerto Vallarta, Jalisco, Mexico. November 1992.

"Spectral distribution of solar UV measurements from SOLSTICE (UARS) observations." J. London. American Geophysical Union; San Francisco, California. December 1992.

"Middle Atmosphere Ozone Response to Solar UV Variations over the Solar Cycle." L. Chen, G. Brasseur, and J. London. IAMAP International Assembly; Yokohama, Japan. July 1993.

"Evolution of the Optical Properties of the 1991 Eruption of Mt. Pinatubo." S. T. Massie and G. E. Thomas. International Symposium on Mt. Pinatubo and its Atmospheric Effects, IAMAP International Assembly; Yokohama, Japan. August 1993.

"The Vertical Variation of the Diurnal and Semidiurnal Ozone Oscillations from UARS MLS Observations." J. London, F. Wu, L. Froidevaux, P. D. Ricaud, and G. E. Peckham. American Geophysical Union; San Francisco, California. December 1993.

"Further Investigation of Middle Atmospheric Ozone response to Solar UV Variations over 27-day Solar Rotations." L. Chen, G. Brasseur, and J. London. American Geophysical Union; San Francisco, California. December 1994.

"Middle Atmosphere Ozone Response to Solar UV Variations over 27 Days." L. Chen, J. London, and G. Brasseur. Global Change in Pacific Asia; Beijing, China. August 1994.

"Mesospheric Water Vapor Variability in the Tropics: Solar Lyman-alpha Forcing." G. E. Thomas, L. Chen, and J. M. Russell III. .Ninth International Symposium on Equatorial Aeronomy, Bali, Indonesia. March 1995.

"The Diurnal Variations of Ozone Over the Equatorial Upper Mesosphere: Theory and Observation." J. London, L. Chen, L. Froidevaux, and J. W. Waters. Ninth International Symposium on Equatorial Aeronomy, Bali, Indonesia. March 1995.

"Mesospheric Water Vapor Variability in the Tropics: Solar Lyman-alpha Forcing." G. Thomas, L. Chen, J. M. Russell III, and G. J. Rottman. IUGG Middle Atmosphere Science Symposium, Boulder, Colorado. July 1995.

"Mesospheric Water Vapor, Ozone and Temperature: Solar Lyman-alpha Forcing." G. E. Thomas, L. Chen, J. M. Russell III, and G. J. Rottman. American Geophysical Union Meeting, San Francisco, California. December 1995.

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Publications Supported by NASA Grant No. NAS5-27263

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